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Dilepton production at SIS energies

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Abstract. In this short review the results of detailed studies for dilepton production from $p + A$ and $A + A$ reactions at SIS energies are presented. The calculations are based on a semi-classical BUU transport model that includes the off-shell propagation of vector mesons and evaluates the width of the vector mesons dynamically. Different scenarios of in-medium modifications of vector mesons, such as collisional broadening and dropping vector meson masses, are investigated and the possibilities for an experimental observation of in-medium effects in $p + A$ reactions at 1–4 GeV are discussed for a variety of nuclear targets.

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The modification of hadron properties in nuclear matter is of fundamental interest (cf. Refs. [1, 2, 3, 4, 5]) as QCD sum rules [4, 5, 6] as well as QCD inspired effective Lagrangian models [1, 2, 3, 7, 8, 9, 10, 11, 12, 13] predict significant changes of the vector mesons (ρ, ω and ϕ) with the nuclear density. A more direct evidence for the modification of vector mesons has been obtained from the enhanced production of lepton pairs above known sources in nucleus-nucleus collisions at SPS energies [14, 15]. As proposed by Li, Ko, and Brown [16] and Ko et al. [17], the observed enhancement in the invariant mass range $0.3 \leq M \leq 0.7$ GeV might be due to a shift of the ρ-meson mass following Brown/Rho scaling [1] or the Hatsuda and Lee sum rule prediction [4]. The microscopic transport studies in Refs. [18, 19, 20, 21, 22] for these systems support these interpretations [16, 17, 23, 24]. However, also more conventional approaches that describe a melting of the ρ-meson in-medium due to the strong hadronic coupling (along the lines of Refs. [7, 8, 9, 10, 13]) were found to be compatible with the CERES data [10, 18, 25].

Dileptons have also been measured in heavy-ion collisions at the Bevalac by the DLS collaboration [26, 27] at incident energies that are two orders-of-magnitude lower than that at SPS. Although the first published spectra [26] based on a lim-

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ited data set are consistent with the results from transport model calculations [28, 29, 30, 31] that include pn bremsstrahlung, π^0, η and Δ Dalitz decay and pion-pion annihilation, a later analysis [27], including the full data set, shows a considerable increase in the cross section, which is now more than a factor of five above these theoretical predictions. This discrepancies remains even after including contributions from the decay of ρ and ω that are produced directly from nucleon-nucleon and pion-nucleon scattering in the early reaction phase [32, 22]. With an in-medium ρ spectral function, as that used in Ref. [25] for dilepton production from heavy-ion collisions at SPS energies, dileptons from the decay of both directly produced ρ's and pion-pion annihilation have been considered, and a factor of two enhancement has been obtained compared to the case of a free ρ-spectral function. In Ref. [33] the alternative scenario of a dropping rho-meson mass and its influence on the properties of the $N(1520)$ resonance has been investigated. Indeed, an incorporation of medium effects leads to an enhancement of the rho-meson yield, however, it was not sufficient to explain the DLS data.

As shown by the transport analysis of the Tuebingen group [34] also another scenario for the in-medium modification, i.e. a possible decoherence between the intermediate mesonic states in the resonance decay, increases the dilepton yield. However, still the region about $M \simeq 0.3$ GeV is underestimeted whereas the yield in the vicinity of the rho-meson peak is overestimated, especially, for C+C collisons. Thus, there is no consistent explaination for the DLS data so far.

An alternative way to provide independent information about the hadron properties in the medium is to use more elementary probes such a pions, protons or photons as incoming particles. In such reactions the nuclear matter is close to the ground state, i.e. at normal nuclear density, however, in-medium effects might be still significant to be observed experimentally.

In Refs. [35, 36], therefore, the study of dilepton production from heavy-ion, pion-nucleus (cf. [21, 37]) and photon-nucleus reactions [38] has been extended to proton-nucleus reactions. Within dynamically calculated width of vector mesons the different scenarios of in-medium modifications and there effect on the dilepton observables has been examined. Moreover, for the first time in transport calculations the off-shell propagation of the vector mesons – adopted from Refs. [39, 40] – has be included consistently.

In this contribution a short overview of the basic futures of off-shell dynamics for rho-meson propagation from Ref. [35] is presented. This is of importance for future transport calculations especially with respect to upcoming experimental data from the HADES Collaboration at GSI.

1. Description of the model

In Ref. [35] the analysis of dilepton production from pA collisions is performed within the BUU approach of Refs. [38, 41]. This model is based on the resonance concept of nucleon-nucleon and meson-nucleon interactions at low invariant energy

$\sqrt{s}$ [42] by adopting all resonance parameters from the Manley analysis [48].

The high energy collisions – above $\sqrt{s} = 2.6$ GeV for baryon-baryon collisions and $\sqrt{s} = 2.2$ GeV for meson-baryon collisions – are described by the LUND string formation and fragmentation model FRITIOF [43]. This aspect is similar to that used in the HSD approach [20, 21, 44] and the UrQMD model [45].

The dilepton production within the resonance model can be schematically presented in the following way:

$$
\begin{aligned}
BB &\rightarrow RX & (1)\\
mB &\rightarrow RX & (2)\\
& R \rightarrow e^+e^-X, & (3)\\
& R \rightarrow mX,\ m \rightarrow e^+e^-X, & (4)\\
& R \rightarrow R'X,\ R' \rightarrow e^+e^-X, & (5)
\end{aligned}
$$

i.e. in a first step a resonance R might be produced in baryon-baryon (BB) or meson-baryon (mB) collisions – (1), (2). Then this resonance can couple to dileptons directly – (3) (e.g., Dalitz decay of the Δ resonance: $\Delta \rightarrow e^+e^-N$) or decays to a meson m (+ baryon) – (4) which produces dileptons via direct decays (ρ, ω) or Dalitz decays (π^0, η, ω). The resonance R might also decay into another resonance R' – (5) which later produces dileptons via Dalitz decay or again via meson decays (e.g., $D_{35}(1930) \rightarrow \Delta\rho,\ \Delta \rightarrow e^+e^-N,\ \rho \rightarrow e^+e^-$). Note, that in the combined model the final particles – which couple to dileptons – can be produced also via non-resonant mechanisms, i.e. 'background' at low and intermediate energies and string decay at high energies.

The electromagnetic part of all conventional dilepton sources – π^0, η, ω and Δ Dalitz decay, direct decay of vector mesons ρ, ω and pn bremsstrahlung – are treated in the same way as described in detail in Ref. [46]– where dilepton production in pp and pd reactions has been studied – and should not be repeated here again.

2. In-medium effects on dilepton production.

2.1. Collisional broadening and in-medium propagation

In line with Refs. [47] the effects of collisional broadening for the vector meson width have been implemented:

$$\Gamma^*_V(M, |\vec{p}|, \rho) = \Gamma_V(M) + \Gamma_{coll}(M, |\vec{p}|, \rho), \tag{6}$$

where the collisional width is given as

$$\Gamma_{coll}(M, |\vec{p}|, \rho) = \gamma\ \rho < v\ \sigma^{tot}_{VN} > . \tag{7}$$

Here $v = |\vec{p}|/E,\ \vec{p},\ E$ are the vector meson velocity, 3-momentum and energy with respect to the target at rest, γ is the Lorentz factor for the boost to the rest frame

of the vector meson, ρ the nuclear density and σ_{VN}^{tot} is the meson-nucleon total cross section calculated within the Manley resonance model [48], while $\Gamma_V(M)$ denotes the vacuum width according to the Manley parametrization [48] (for details see Ref. [38]). In Eq. (7) the brackets stand for an average over the Fermi distribution of the nucleons.

While propagating through the nuclear medium the total width of the vector meson Γ_V^* (6) changes dynamical and its spectral function is modified according to the real part of the vector meson self energy $Re\Sigma^{ret}$, as well as by the imaginary part of the self energy ($\Gamma_V^* \simeq -Im\Sigma^{ret}/M$) following

$$A_V(M) = \frac{2}{\pi}\ \frac{M^2\Gamma_V^*}{(M^2 - M_0^2 - Re\Sigma^{ret})^2 + (M\Gamma_V^*)^2}, \tag{8}$$

which is the in-medium form for a boson spectral function.

Since the vector mesons are produced at finite density in line with the mass-distribution (8) with $\Gamma_V^* \neq \Gamma_V$ in the kinematical allowed mass regime, their spectral function has to change during propagation and to merge the vacuum spectral function when propagating out of the medium.

In Ref. [35] the general off-shell equations of motion from Refs. [39, 40] have been employed which for test particles with momentum $\vec{P}_i$, energy ε_i at position $\vec{X}_i$ read

$$\frac{d\vec{X}_i}{dt} = \frac{1}{2\varepsilon_i}\left[2\,\vec{P}_i + \vec{\nabla}_{P_i}\,Re\Sigma_{(i)}^{ret} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma_{(i)}^{ret}}{\Gamma_{(i)}}\,\vec{\nabla}_{P_i}\,\Gamma_{(i)}\right], \tag{9}$$

$$\frac{d\vec{P}_i}{dt} = \frac{1}{2\varepsilon_i}\left[\vec{\nabla}_{X_i}\,Re\Sigma_i^{ret} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma_{(i)}^{ret}}{\Gamma_{(i)}}\,\vec{\nabla}_{X_i}\,\Gamma_{(i)}\right], \tag{10}$$

$$\frac{d\varepsilon_i}{dt} = \frac{1}{2\varepsilon_i}\left[\frac{\partial Re\Sigma_{(i)}^{ret}}{\partial t} + \frac{\varepsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma_{(i)}^{ret}}{\Gamma_{(i)}}\,\frac{\partial\Gamma_{(i)}}{\partial t}\right], \tag{11}$$

where the notation $F_{(i)}$ implies that the function is taken at the coordinates of the test particle, i.e. $F_{(i)} \equiv F(t, \vec{X}_i(t), \vec{P}_i(t), \varepsilon_i(t))$. In Eqs. (9)-(11) $Re\Sigma^{ret}$ denotes the real part of the retarded self energy while $\Gamma = -Im\Sigma^{ret}/2$ stands for the imaginary part in short-hand notation. Note, that in (9)-(11) energy derivatives of the self energy Σ^{ret} have been discarded (cf. [39, 40]).

Furthermore, following Ref. [39] and using $M^2 = P^2 - Re\Sigma^{ret}$ as an independent variable instead of the energy $P_0 \equiv \varepsilon$, Eq. (11) turns to

$$\frac{dM_i^2}{dt} = \frac{M_i^2 - M_0^2}{\Gamma_{(i)}}\,\frac{d\Gamma_{(i)}}{dt} \tag{12}$$

for the time evolution of the test-particle i in the invariant mass squared [39, 40].

Apart from the propagation in the real potential $\sim Re\Sigma/2\varepsilon$ the equations (9) – (12) include the dynamical changes due to the imaginary part of the self energy $Im\Sigma^{ret} \sim -M\Gamma_V^*$ with Γ_V^* from (6). It is worth to mention that the deviation from the pole mass, i.e. $\Delta M^2 = M^2 - M_0^2$, follows the equation

$$\frac{d}{dt}\Delta M^2 = \frac{\Delta M^2}{Im\Sigma^{ret}}\ \frac{d}{dt}Im\Sigma^{ret}, \tag{13}$$

which expresses the fact that the off-shellness in mass is proportional to the total width Γ_V^*. Note, furthermore, that the equations of motion (9) – (12) conserve the particle energy ε if the self energy Σ^{ret} does not depend on time explicitly (cf. Refs. [39, 40]), which is approximately the case for $p + A$ reactions.

2.2. 'Dropping' vector meson mass

In order to explore the observable consequences of vector meson mass shifts at finite nuclear density the in-medium vector meson masses are modeled according to the Hatsuda and Lee [4] or Brown/Rho scaling [1] as

$$M^* = M_0\left(1 - \alpha\frac{\rho(\vec{r})}{\rho_0}\right), \tag{14}$$

where $\rho(\vec{r})$ is the nuclear density at the resonance decay, $\rho_0 = 0.16$ fm^{-3} and $\alpha \simeq 0.18$ for the ρ and ω. The choice (14) corresponds to

$$Re\Sigma^{ret} = M_0^2\left(\left(\alpha\frac{\rho}{\rho_0}\right)^2 - 2\alpha\frac{\rho}{\rho_0}\right) \tag{15}$$

in (9) – (12), which is dominated by the attractive linear term in ρ/ρ_0 at nuclear matter density ρ_0.

The in-medium vector meson masses M^* (14) in principle have to be taken into account in the production part as well as for absorption reactions and for propagation. This is implemented for the low energy reactions with nucleon resonances. Note, however, that the vector mesons produced by the FRITIOF model – as implemented in the transport approach [38] – have masses according to the free spectral function. This approximation might not be severe since the vector mesons from string decay at high energy have high momenta with respect to the target nucleus where pole-mass shifts are expected to be small [13, 49]. Furthermore, the $N\rho$-width of the baryonic resonances at finite density [38] has not been modified. Such modifications are out of the scope of the present model.

3. Dilepton spectra from $p + A$ collisions from 1–4 GeV

In Fig. 1 the calculated dilepton invariant mass spectra $d\sigma/dM$ are presented for $p + Pb$ collisions from 1.0 – 4 GeV (including an experimental mass resolution ΔM

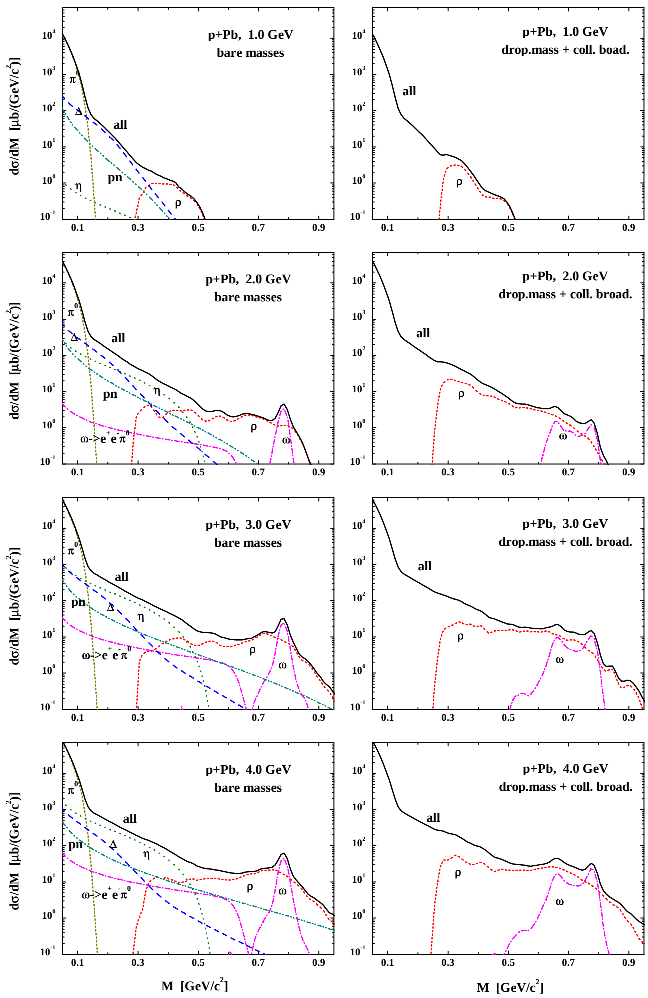

Fig. 1. The calculated dilepton invariant mass spectra $d\sigma/dM$ for $p+Pb$ collisions from 1.0 – 4 GeV (including an experimental mass resolution of 10 MeV) without in-medium modifications (bare masses) – left part, and applying the collisional broadening + dropping masses scenario – right part.

= 10 MeV) without in-medium modifications (bare masses) – left part, and applying the collisional broadening + dropping mass scenario – right part. The dominant contribution at low M ($> m_{\pi^0}$) is the η Dalitz decay, however, for $M > 0.4$ GeV the dileptons stem basically all from direct vector meson decays (ρ and ω).

In order to see the differences between the results from the left and right panels

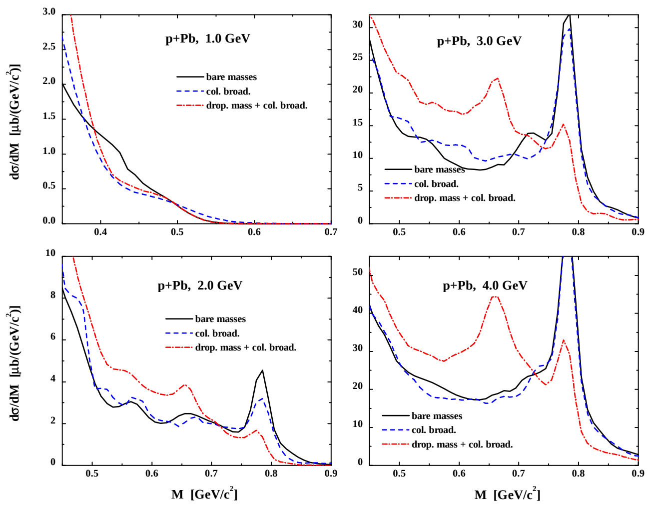

Fig. 2. The comparison of different in-medium modification scenarios, i.e. collisional broadening (dashed lines) and collisional broadening + dropping vector meson masses (dash-dotted lines), with respect to the bare mass case (solid lines) on a linear scale for $p + Pb$ from 1–4 GeV.

of Fig. 1, a comparison of the different in-medium modification scenarios is shown in Fig. 2, i.e. collisional broadening (dashed lines) and collisional broadening + dropping vector meson masses (dash-dotted lines), with respect to the bare mass case (solid lines) on a linear scale for $p + Pb$ from 1–4 GeV.

Whereas collisional broadening of the ρ spectral function again gives no clear signal within the numerical accuracy achieved the 'dropping mass' scenario leads to a pronounced modification of the spectral shape. A strong reduction of the dilepton yield in the vector meson pole mass region around 0.77 GeV is observed since most of the ρ's and ω's now decay in the medium approximately at density ρ_0. This leads to a pronounced peak around $M \approx 0.65$ GeV, which can be attributed to the in-medium ω decay since the ρ spectral strength is distributed over a wide low mass regime. The situation is very reminiscent of dilepton spectra from $\pi + A$ and $\gamma + A$ reactions in Refs. [21, 37, 38]. Especially when comparing dilepton spectra from C and Pb targets, it should be experimentally possible to distinguish an in-medium mass shift of the ω meson by taking the ratio of both spectra.

4. Summary

In this contribution a short review of the detailed study in Ref. [35] on dilepton production has been presented within the framework of the coupled-channel BUU model employing a full off-shell propagation of the vector mesons in line with Refs.

[39, 40]. Different scenarios of in-medium modifications of vector mesons, such as collisional broadening and dropping vector meson masses, have been investigated and the possibilities for an experimental observation of in-medium effects in $p + A$ reactions has been discussed.

Dilepton spectra from $p + A$ reactions will be measured by the HADES Collaboration at GSI Darmshtadt with high mass resolution and good accuracy. In this respect predictions for the dilepton invariant mass spectra, transverse momentum and rapidity distributions for $p + A$ collisions from 1 to 4 GeV have been made in Ref. [35] employing different in-medium scenarios. It has been found that the collisional broadening + 'dropping mass' scenario leads to an enhancement of the dilepton yield in the range $0.5 \le M \le 0.75$ GeV and to a reduction of the ω-peak, which is most pronounced for heavy systems (up to a factor 2 for $p + Pb$ at 3–4 GeV).

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